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An Analysis of CCS Investment under Uncertainty

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Abstract

Carbon capture and storage (CCS) is one of the most important measures for emission reductions due to the cost effectiveness and huge potentials. In general break even costs based on normal discounted cash flow (DCF) method are referred in a discussion on CCS diffusions. These evaluations with static and perfect foresight assumptions indicate that the break even costs for CCS diffusions are moderate, around US\$35/tCO_2. In contrast it seems that an early large-scale commercialization of CCS is far from ideal due to technical, economical, social barriers and their uncertainties. In terms of economical aspect, carbon value and fuel price are very uncertain.

In this study we focus on cost analysis of power plant replacement and CCS investment as a replacement for an aged coal plant. In this analysis carbon price and gas price are explicitly uncertain. Using a *real options approach* we found the threshold between “waiting” and “investment right now”. “Waiting” means that the firm continues to operate the aged coal plant, which has low thermal efficiency and high CO_2 intensity. “Investment right now” means that the firm throws out another investment options.

The results indicate that it requires substantially higher carbon prices, e.g., US\$70/tCO_2, for CCS diffusions under uncertainty. The threshold for CCS investment is also affected by gas price. For example, in the middle range gas price (around US\$10/GJ), the threshold can be over US\$100/tCO_2. In addition possibility of free allocation based on absolute historical emissions (grandfathering) makes it more difficult to invest CCS. On the other hand existing (aged) coal plants have strong competitiveness under uncertainty. It seems that this is consistent with real situations in each country. Reducing uncertainty of climate policy is the key to an early CCS diffusion.

"Keywords: uncertainty; investment; carbon capture and storage; aged coal plant; real options approach"

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1. Introduction

The orthodox theory of investment decision has been considered discounted cash flow (DCF) method. In the discussion on CCS diffusions, break even costs based on the DCF method are mainly referred. Figure 1 is an example for choice between a new coal and a new gas plants (+CC(S)). It indicates that US\$35/tCO_2 is sufficient to invest in CC(S).

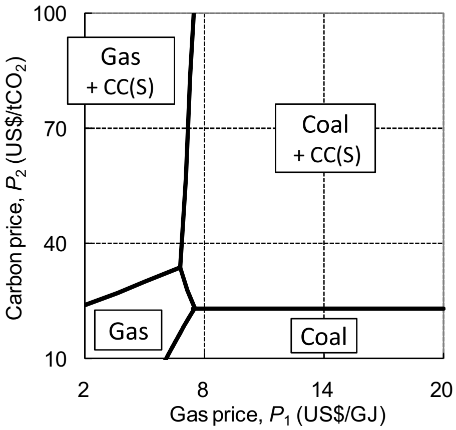

Figure 1 An example of break even costs for a new plant based on normal DCF method

Note) This figure is based on common parameters of later analysis shown in Table 1 and 2 except the lead time of gas plant, four years, which is same period of coal plant. A discount rate of 5%/yr is adopted. Gas and carbon prices deterministically increase by 1.5%/yr and 3.2%/yr respectively.

On the other hand, firm's investment decisions seem not to follow the DCF's story. A firm intends to wait to invest until the expected value of invest becomes sufficiently deep in the money. In the power and CCS context, they hesitate to invest new power plant and CC(S) in the real world. A real options approach is explicitly premised on uncertainty of the cash flow, irreversibility of the capital cost and the future optimal strategy. We can explain these firms' behaviors using a real options approach (Dixit and Pindyck (1994)).

In this paper, we focus a firm owing aged coal-fired power plant. The firm has options to invest in four types of new power plant as described below as a replacement for the aged coal plant;

i) coal plant,
ii) coal plant + CC(S),
iii) gas plant, and
iv) gas plant + CC(S).

The firm can also refurbish the aged coal plant and avoid a new plant construction. In the case of refurbishment, they can select

v) refurbishment of the aged coal plant, or
vi) refurbishment of the aged coal plant + CC(S) retrofit.

We find the optimal investment behavior, cost minimization, subject to stochastic natural gas price, P_1, and carbon price, P_2, under an emission trading system. IEA (2007) discussed a similar framework and explicitly treated each stochastic variable for quantitative analysis. This study explicitly treats two variables at the same time as shown in Oda et al. (2004) and improves previous studies.

2. Framework of the model analysis

To simply the model analysis we focus on the firm that has the characteristics as described below.

i) The firm supplies base load electricity with their associated company. The firm must keep the same level of electricity output. Electricity price does not affect the firm decisions directly.

ii) The firm is involved in an emission trading system. They have a certain volume of free allocation in the early stage.

iii) The firm has an advantage for CCS investment and they must charge only capture costs. There is no cost charge for transport and storage of CO_2 since it is utilized for enhanced oil recovery.

iv) The firm is interested in low cost power generation including CO_2 cost.

v) The firm wants to minimize the expected discounted total cost under gas price and carbon price uncertainties.

vi) The firm has risk-neutral preference.

The firm's decision tree with discrete time and assumed schedule of the analysis are shown in Figure 2. If the firm avoids a new plant construction, two times refurbishments are needed at t=8 and 24. The firm can retrofit a CC(S) facility at the same time of first refurbishment. The lead time for a new plant construction is explicitly considered in this analysis. The lead time means the period from firm's investment decision to operation start. The lead times for gas and coal plants are two and four years respectively.

In terms of allocation schedule, we set the (extreme) two cases;

i) *Emission cap with perfect foresight case* and

ii) *Historical-based emission cap case*.

In the *Emission cap with perfect foresight case*, the firm perfectly knows that they will obtain the notified volume of fee allocation shown in Figure 2; however, there is no chance to obtain additional fee allocation. In the *Historical-based emission cap case*, the firm knows that "grandfathering" free allocation will be divided in the further duration ($10 \le t \le 25$). This means that the firm surely obtains free allowance based on absolute historical emissions ($8 < t \le 10$); however, there is no chance to obtain additional fee allocation even if they have invested in CC(S).

3. Formulation and numerical analysis

In this study, we assumed that natural gas price, P_1, and carbon price, P_2, follow the geometric Brownian motion:

$$dP_1 = a_1 P_1 dt + b_1 P_1 dz_1, \quad dP_2 = a_2 P_2 dt + b_2 P_2 dz_2 \tag{1}$$

where a_i is expected instantaneous drift rate of P_i; b_i is instantaneous volatility rate of P_i; and dz_i is the increment of a Wiener process. Suppose ε_t has zero mean and unit standard deviation, we can write $dz_i = \varepsilon_t (dt)^{1/2}$, $E[(dz_i)]=0$, $E[(dz_i)^2]=dt$, and $E[(dz_1)(dz_2)]=\rho_{12} \bullet dt$, where ρ_{12} is the coefficient of correlation between P_1 and P_2.

Since the model framework treats a finite time horizon and multiple variables, we must depend on numerical solution to solve a value function. This study uses dynamic programming shown in Dixit and Pindyck (1994). Suppose F_t denotes the expected net present value of the cash flow when the firm makes all decisions optimally from time t onwards, the Bellman equation with discrete time is

$$\begin{aligned}
F_t &= \min\left[V_{gas,t},\ V_{gas+ccs,t},\ V_{coal,t},\ V_{coal+ccs,t},\ 8760\,CF\cdot C_{aged}\cdot\Delta t + E[F_{t+\Delta t}]\cdot\exp(-r\Delta t)\right] && (0 \le t \le 4)\\
F_t &= \min\left[V_{gas,t},\ V_{gas+ccs,t},\ 8760\,CF\cdot C_{aged}\cdot\Delta t + E[F_{t+\Delta t}]\cdot\exp(-r\Delta t)\right] && (4 < t \le 6)\\
F_t &= 8760\,CF\cdot C_{aged}\cdot\Delta t + E[F_{t+\Delta t}]\cdot\exp(-r\Delta t) && (6 < t < 8)\\
F_t &= \min\left[V_{aged,t},\ V_{aged+ccs,t}\right] && (t = 8)
\end{aligned} \tag{2}$$

where $V_{gas(+CCS),t}$ is expected total cost, including running cost of aged coal plant during the lead time, when the firm decides to invest the new gas plant (+CCS) at time t; $V_{coal(+CCS),t}$ is expected total cost of the new coal plant; $V_{aaged(+CCS),t}$ is expected total cost of the aged coal plant refurbishment; C_{aged} is O&M and fuel cost of the aged coal plant; r is discount rate; Δt is a time interval. In the numerical calculation a relatively short time interval of 0.02 year is used. We can easily evaluate $V_{gas(+CCS),t}$, $V_{coal(+CCS),t}$ and $V_{aged(+CCS),t}$ with static calculation. To approximate Brownian motion, we use lattice model with two variables, which is extension of the lattice model with one variable developed by Cox and Miller (1965).

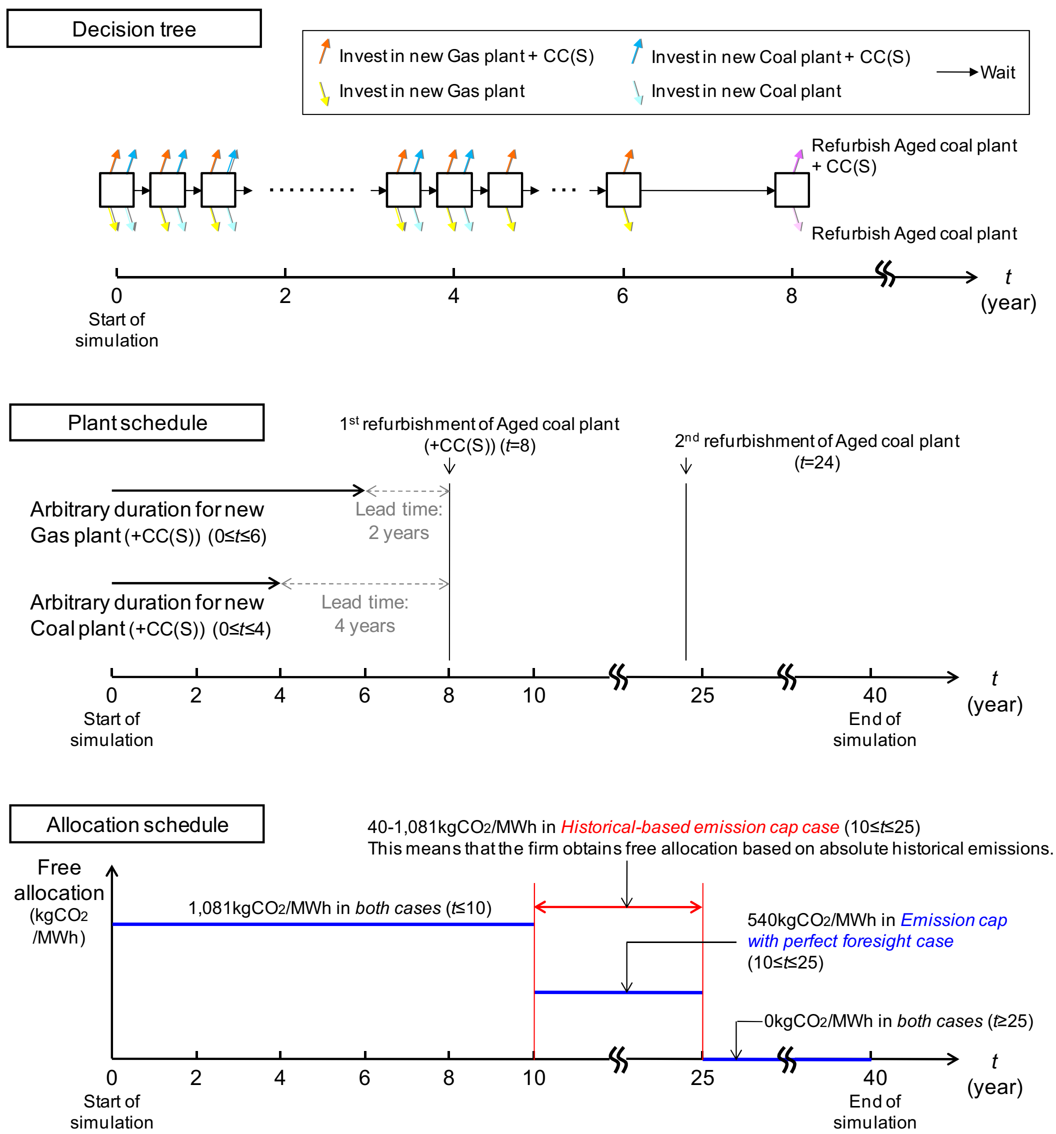

Figure 2 Assumed schedule for plant and allowance

4. Input Parameter

Table 1 shows the assumed input parameters for power plants in this analysis. These parameters are basically based on David and Herzog (2000), Hamilton et al. (2008) and NEA (2010) as a typical one for international perspectives. Coal prices are taken to be fixed for the duration of this analysis at US$3.4/GJ or around US$90/t, which is based on OECD steam coal import cost. The firm can extend the life of the aged coal plant with a certain capital cost shown in Table 1. Capital costs of CC(S) include the additional gross power capacity; however, it excludes initial costs for transport and storage since the total volume of captured CO_2 is utilized for enhanced oil recovery.

As for stochastic gas price, P_1, and carbon price, P_2, this analysis uses the parameters shown in Table 2. For the setting we referred statistical analysis based on historical data, future perspectives (e.g., US DOE/EIA, 2010) and results of energy systems model under global CO2 emission target (e.g., Oda et al., 2008). A discount rate of 5%/yr is adopted throughout the study.

Table 1 Input parameters for power plants

	Aged Coal plant ($0\leq t\leq 8$)	Aged Coal plant After refurbishment ($t\geq 8$)		New Coal plant Ultra-supercritical PCC		New Gas plant Combined cycle gas turbine	
	-	No capture	CC(S)	No capture	CC(S)	No capture	CC(S)
Net thermal efficiency (LHV), %	31.5%	31.5%	28.3%	41.1%	34.8%	57.0%	50.5%
CO_2 intensity, $kgCO_2/MWh$	1,081	1,081	120	828	98	355	40
Capacity factor, %	85%	85%	85%	85%	85%	85%	85%
Fuel price, US$/GJ	3.4	3.4	3.4	3.4	3.4	P_1	P_1
Overnight capital cost, US$/kW	-	350	2,210	2,134	3,838	1,069	1,951
Fuel cost, US$/MWh	38.9	38.9	43.2	29.8	35.2	-	-
O&M cost, US$/MWh	11.0	11.0	18.0	6.0	13.0	4.5	7.3

Table 2 Parameters for stochastic gas and carbon prices

	Expected drift rate, a_i	Volatility rate, b_i	Coefficient of correlation, ρ_{12}
Gas price, P_1	1.5%/yr	0.27	0.20
Carbon price, P_2	3.2%/yr	0.34	

5. Results of the numerical calculation

Simulation results are shown in Figure 3. It is quite different from Figure 1, which consists of straight lines only. In most periods except time t=8, the area of "waiting" is so large. This means that the firm continues to operate the aged coal plant that has low energy efficiency and high CO_2 intensity because it has an economic rationality under uncertainties of gas and carbon prices. In other word, it is reasonable to keep the option to invest in four types' power plants and refurbishment of the aged coal plant. The area of "waiting" splits the rounded investment areas for a new plant, which stay at a corner in Figure 3 due to the interaction effect of multiple options (t<6). In the time t=6, which is the last period to invest new gas plant (+CC(S)), the investment areas for gas touch each other by straight line.

Even in the *Emission cap with perfect foresight case*, investment in CC(S) requires higher carbon prices than that in normal DCF method in most figures. The threshold for a new coal + CC(S) is relatively low in the early stage (t=0). This is because it is cost effective to take a long-term operation for a capital intensive plant and the end of simulation is fixed at t=40 in this study. Even in the time t=0, the threshold for a new coal + CC(S) is around US$70/$tCO_2$ where gas price is US$13/GJ. In the middle range gas price from US$7/GJ to US$12/GJ, US$100/$tCO_2$

is not sufficient to invest CC(S) right now. This means that the expected value of investment for a new plant + CC(S) never overcome the expected value of keeping the three options; a new gas + CC(S), a new coal + CC(S) and CC(S) retrofit to aged coal plant.

In the *Historical-based emission cap case*, it is more difficult to invest in CC(S). At the time *t*=4, the threshold for a new coal plant + CC(S) shifts over US\$100/tCO_2 and disappears from the Figure 3. On the other hand, a new plant (w/o capture) takes more competitiveness due to the free allocation based on historical emissions (grandfathering). The area of a new coal plant (w/o capture) spreads in the area of low carbon and high gas prices at time *t*=3 and 4. The results in the *Historical-based emission cap case* indicate the importance of allocation scheme that each firm expects.

In the both cases, the threshold for a new gas + CC(S) is very sensitive to gas price rather than carbon price. The threshold is steep as shown in Figure 3. For a diffusion of new gas + CC(S) it requires both certain climate policy and inexpensive gas supply. Normal DCF method indicates that only carbon price is important for the CCS diffusions shown in Figure 1; however, the level of gas price and its uncertainty are also key factors for the CCS diffusions.

6. Conclusions

In a discussion on CCS diffusions, break even costs based on normal discounted cash flow (DCF) are referred. It indicates that the break even costs for CCS diffusions are moderate, around US\$35/tCO_2. On the other hand, it seems that many firms hesitate to invest in CCS commercialization at this moment. The gap between reality and ideal could be derived from technical, economical, and social barriers and their uncertainties.

In this study we focus on cost analysis of power plant replacement and CCS investment as a substitute for an aged coal plant under stochastic gas and carbon prices. Using a *real options approach* we found the threshold between “waiting” and “investment right now”.

The results indicate that it requires substantially higher carbon prices, e.g., US\$70/tCO_2, for CCS diffusions. In the middle range gas price from US\$7/GJ to US\$12/GJ, carbon prices in the range from US\$70/tCO_2 to US\$100/tCO_2 are not sufficient to invest CC(S) right now. This is because the expected value of keeping the multiple options exceeds the expected value of investment. In addition possibility of free allocation based on absolute historical emissions (grandfathering) makes it more difficult to invest CCS. Allocation scheme that each firm expects is also the key factor.

The results also indicate that an existing (aged) coal plant has strong competitiveness under uncertainty. It seems that this is consistent with real situations in each country. This study illustrates the quantitative representation for these real situations; however, this is the first step for dealing with complexity of the real world. In addition to additional support by government, reducing uncertainty of climate policy is the key to an early CCS diffusion.

References

Cox, D.R., and H.D. Miller, The Theory of Stochastic Processes. London: Chapman and Hall, (1965)
David, J., and H. Herzog, The Cost of Carbon Capture. Proceedings of the GHGT-5, (2000)
Dixit, A.K., and R.S. Pindyck, Investment under Uncertainty. Princeton, NJ: Princeton University Press, (1994)
Hamilton, M.R., H.J. Herzog and J.E. Parsons, Cost and U.S. Public Policy for New Coal Power Plants with Carbon Capture and Sequestration. Proceedings of the GHGT-9, 1(1), 4487-94, (2008)
IEA, Climate Policy Uncertainty and Invest Risk, In support of the G8 Plan of Action, Paris, (2007)
NEA, Projected Costs of Generating Electricity: 2010 Update, OECD/Nuclear Energy Agency. OECD Publishing, Paris, (2010)
Oda, J., R. Matsuhashi and Y. Yoshida, The Decision to Invest in Emissions Reduction Technologies based on the Real Options Approach, Proceedings of the GHGT-7, (2004)
Oda, J., K. Akimoto, F. Sano, T. Homma and T. Tomoda, Diffusion of CCS and Energy Efficient Technologies in Power and Iron & Steel Sectors, Proceedings of the GHGT-9, 1(1), 155-61, (2008)
US DOE/EIA, The International Energy Outlook 2010, (2010) http://www.eia.doe.gov/oiaf/ieo/

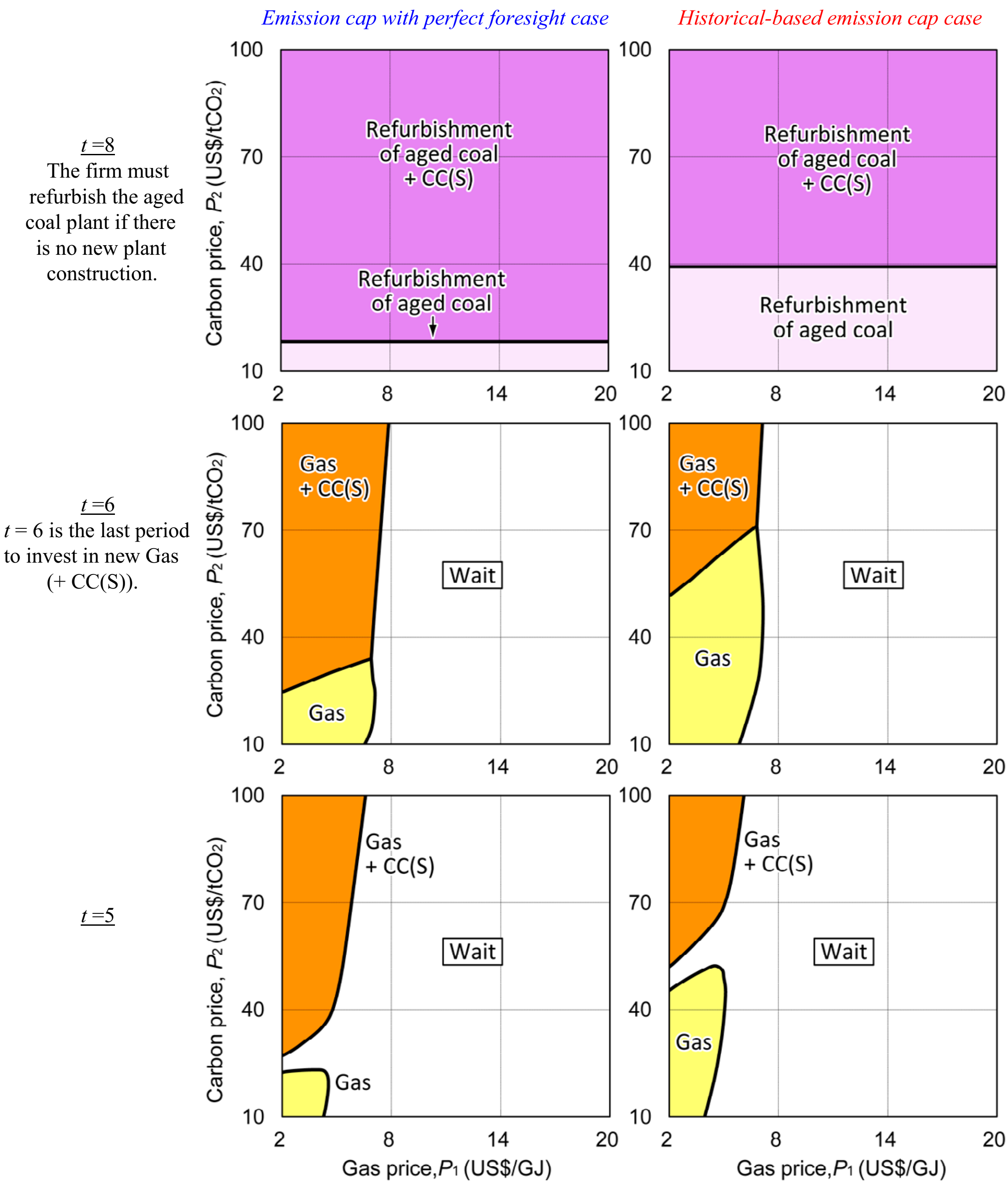

Figure 3 Results of the threshold between “waiting” and “investment right now”

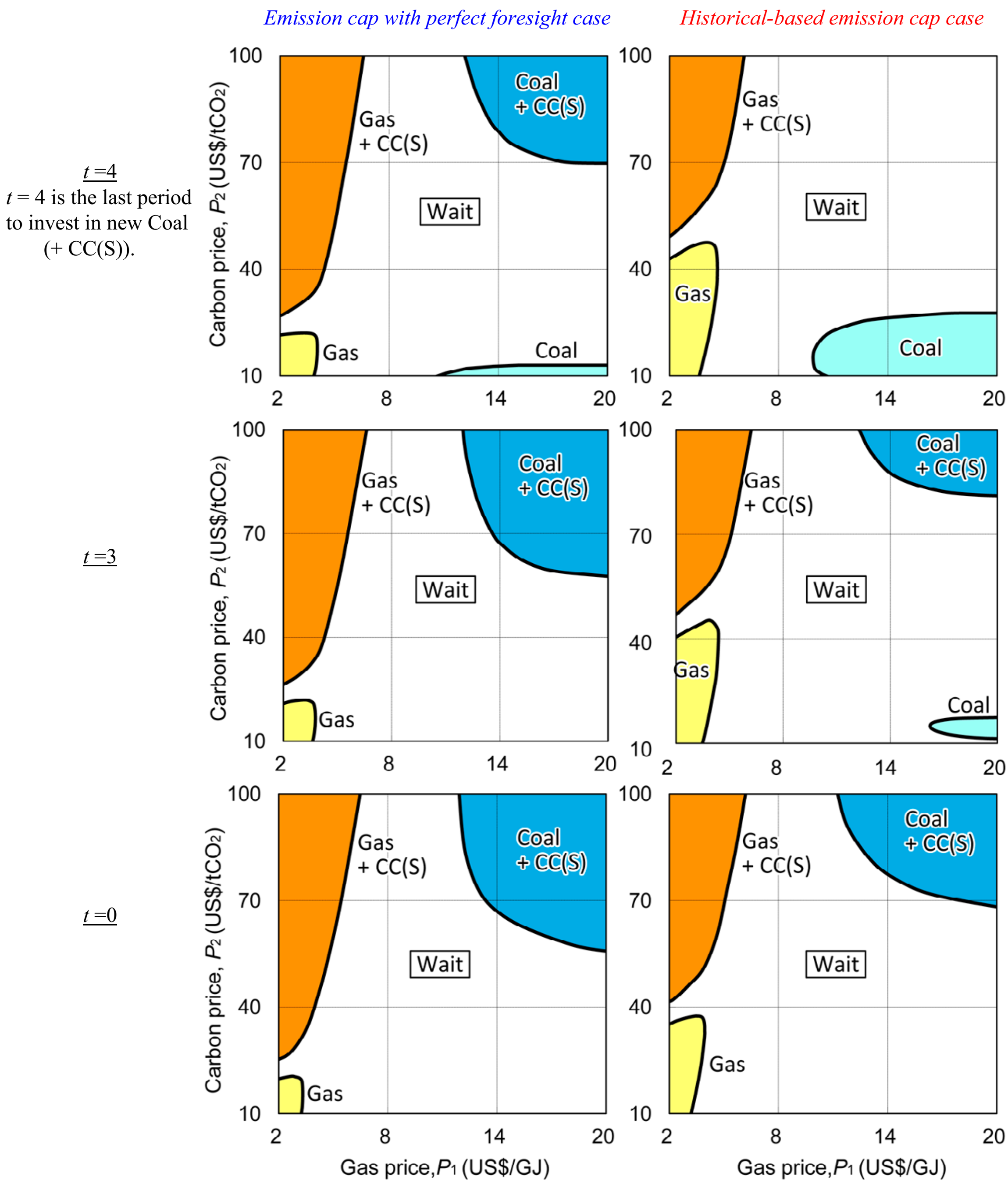

Figure 3 Results of the threshold between “waiting” and “investment right now” (*continued.*)